LCA Methodology

Marginal Production Technologies for Life Cycle Inventories

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Abstract

Marginal technologies are defined as the technologies actually affected by the small changes in demand typically studied in prospective, comparative life cycle assessments. Using data on marginal technologies thus give the best reflection of the actual consequences of a decision. Furthermore, data on marginal technologies are easier to collect, more precise, and more stable in time than data on average technologies. A 5-step procedure is suggested to identify the marginal technologies. The step-wise procedure first clarifies the situation in which the marginal should apply, and then identifies what specific technology is marginal in this situation. The procedure is illustrated in two examples: European electricity production and pulp and paper production.

Keywords: European electricity scenario, marginal technology, LCA; Life Cycle Assessment (LCA), methodology, marginal technology; marginal technology, LCA; pulp and paper production, marginal technology, LCA

Box 1: Definitions

Marginal technology: The technology actually affected by a small change in demand.

Constrained technology: A technology whose capacity can not be adjusted in response to changes in demand, e.g. due to lack of raw materials, quality constraints, political constraints, or the lack of a market for co-products.

Long-term: A period long enough to include replacement of capital equipment (as opposed to short-term).

Long-term marginal technology: The technology installed or dismantled due to expected long-term changes in demand.

Short-term marginal technology: An existing technology changing its output due to small changes in demand.

Foreground process: A process whose production volume is affected directly by a change in production volume of the studied system.

Most preferred, unconstrained technology: The technology with the lowest long-term production costs, taking into account constraints and non-monetarised costs, as perceived by those who decide about the capacity adjustment in question.

1 Introduction

The consequence of a comparative life cycle assessment is typically that a choice is made between different existing or potential product systems. Thus, it is the effect of this choice, which it is desired to investigate in the life cycle assessment. The technologies to include in the study should be the technologies actually affected by the choice. A choice between two or more products implies a reduction in demand for some production processes and an increase in demand for other processes. The changes in demand are normally regarded as being small compared to the production in society in general, which is therefore assumed unchanged. This means that the change is analysed in isolation under a *ceteris paribus* condition. The technology actually affected by small (marginal) changes is called the marginal technology (see *Box 1* for definitions and *Box 2* for a simple example of a marginal technology). If the studied change is larger, it may be necessary to use scenario techniques, which include the necessary societal changes.

Although it has been argued for some years (see e.g. Weidema, 1993) that for comparative life cycle assessments the actual environmental impacts are most correctly modelled by using environmental data on the marginal production facilities, only few life cycle assessments have until now applied marginal technologies, even when their goals have been clearly comparative.

One explanation for this may be that historically the technique of life cycle assessment is based in energy analysis (Weidema, 1997), an engineering discipline aimed at accounting for the energy directly or indirectly expended for production of a product. Energy analysis and life cycle assessment have developed somewhat isolated from the traditions of economical analyses, where the study of marginal changes are commonplace.

Recently, the distinction has become increasingly clear (Tillman, 1998; Weidema, 1998) between the *retro*spective life cycle assessments of the accountancy type (typically ap-

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plied for hot-spot-identification and product declarations) and the *pro*spective, comparative life cycle assessments, which study possible future changes between alternative product systems (typically applied in product development and in public policy making).

Box 2: Simple example of a marginal technology

Most Norwegian electricity is produced by hydro-power plants. But if we analyse a change that involves a small increase in electricity consumption in a Norwegian industry, the actual power plant that will be used to produce this small (marginal) amount of additional electricity is likely to be a fossil-fuel based power plant. This is because Norwegian hydro-power is in practice limited to the present capacity. As the increased demand for electricity can not be covered by hydro-power, it causes an increase in the Norwegian import of (fossil-fuel based) electricity from Denmark (since adequate transmission capacity is available between the two countries) or alternatively, the Norwegians may decide to build a fossil-fuel based power station to make up for the increase. In both instances, the technology will be the same (modern, unconstrained), but the geographical position of the marginal power plant may be determined by other factors. The logic is equivalent if you move from a high electricity demand to a lower electricity demand. This would mean that less electricity would have to be imported from Denmark or alternatively, that less non-hydro Norwegian electricity would be needed.

In the ISO 14041 standard, the distinction between retrospective, accountancy type assessments and prospective, comparative assessments is not completely clear. However, the stepwise procedure in ISO 14041 for dealing with co-products, is a reflection of the different needs for allocation methods among these two types of life cycle assessments. Co-product allocation by e.g. economic relationships, being the last procedural step in the standard, is actually relevant only for life cycle assessments of the retrospective type, where no system expansion is possible and a full (100%) allocation of the environmental inputs and outputs is required. Similarly, avoiding allocation by expanding the product system, which is the first procedural step in the standard, is only possible for comparative studies, since a system expansion involves addition of the processes actually affected when switching between two or more analysed systems, i.e. marginal production processes. Thus, the 5-step procedure for identifying marginal technologies, which is presented in this paper, can also be seen as a description of how to fulfil the requirement in ISO 14041 to justify the required system expansions.

Even when the relevance of marginal technologies has been recognised, their use have not been encouraged (see e.g. Udo de Haes et al., 1996), the reason seemingly being that the correct identification of the marginal production has been regarded as too difficult. Since the result of a life cycle assessment may be strongly influenced by the choice of which unit processes (and consequently which technologies) to include in the investigated product systems (see e.g. Lindfors et al., 1995), the use of data for average production facilities has been seen as a way to reduce this modelling uncertainty. Another problem is that those life cycle assessments, which have applied data for marginal production facilities (see e.g. Tillman et al., 1998), have done so practically without documentation and justification of the way in which these marginal technologies were identified.

The 5-step procedure, which we present in this paper, aims at overcoming any perceived difficulties in identifying the marginal technologies. In fact, we have found that collecting truly representative, average data is much more cumbersome than identifying and collecting data for marginal technologies. Furthermore, by nature average data have a higher inherent uncertainty and are less stable in time than data for the marginal production. This is also demonstrated by the examples presented in this article. In those instances where the marginal technology can easily be determined beyond reasonable doubt, the use of average data in a prospective, comparative study may actually introduce an unnecessary bias and give rise to misleading conclusions. For such studies, average data can at best be regarded as approximations for marginal data.

2 The Suggested Procedure

The procedure, which we present here, essentially aims at answering two questions:

1) What is the situation, in which the studied change in demand occurs?

2) In the situation identified in question 1, what specific technology is affected by the change?

The procedure is composed of five steps, illustrated in **Figure 1**, the first three (step a-c) aimed at describing the situation in which the change occurs, and the last two (step d-e) to identify the specific technology affected.

The five steps are now described in more detail:

(a) What time horizon does the study apply to?
One should distinguish between short-term, when studying changes which take place within the existing production capacity and which are not expected to affect capital investment (installation of new machinery or phasing out of old machinery), and long-term, when studying changes that are expected to affect capital investment.

Most life cycle assessments study changes, which do affect capital investment. This is most obvious for technologies with a short capital cycle (fast turnover of capital equipment, as e.g. in the electronics and polymer industries) and in free market situations (where market signals play a major role when planning capacity adjustments). But also for technologies with a long capital cycle (e.g. in the building and

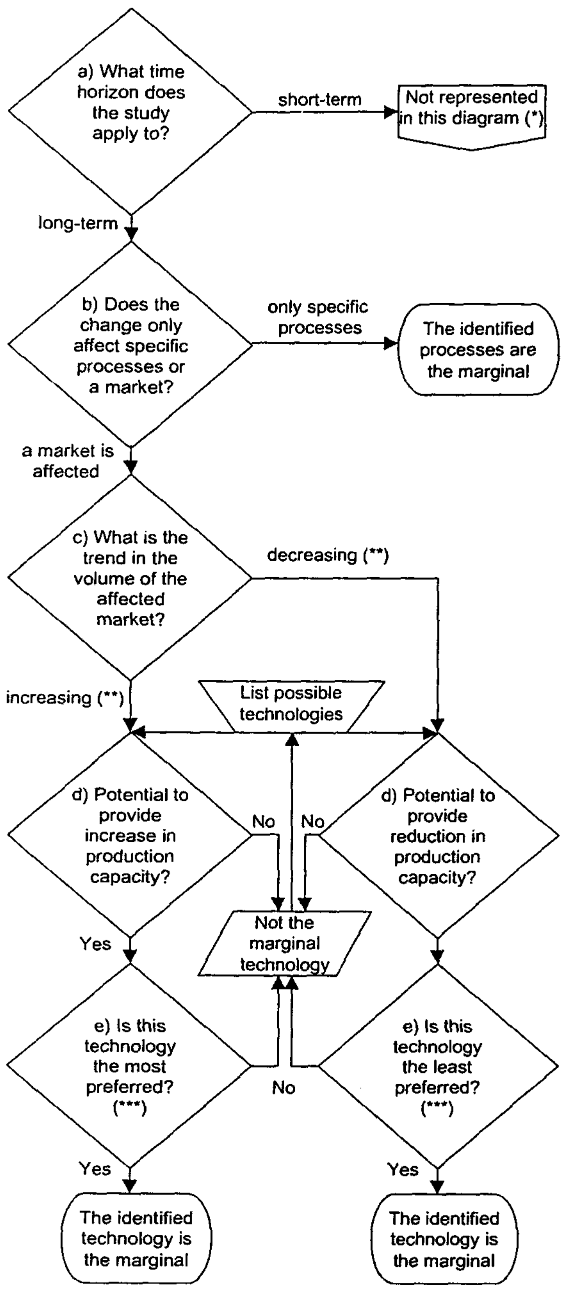

Figure 1: Decision tree showing the 5-step procedure

(*) Short term marginals may be identified using a similar decision tree as the one presented here. The difference between the two diagrams would be that instead of increases and decreases in capacity, the short term diagram would ask for increases and decreases in production output within existing capacity

(**) To be precise, the option "decreasing" is only relevant if the market volume is decreasing *more* than the decrease resulting from regular, planned phasing out of capital goods. Consequently, the option "increasing" is also valid when market volumes decrease at a rate less than the regular capital replacement rate

(***) The preference implied here, relates to the expected long-term production costs taking into account all externalities relevant for the one who decides about the capacity adjustment. See the text on step e) for further elaboration of this point

paper industries), the individual decisions of a large amount of individual enterprises implies that capacity adjustments may be seen as a continuous process affected by the current and expected trends in the market volume. Adjustments which have short-term effects only, i.e. affect only capacity utilisation, but not capacity itself, occur in exceptional situations where changes have in-house effects only (no effect on commercial in- or outputs), where no capital investment is planned (e.g. industries in decline), or where the market situation has little influence on capacity adjustments (i.e. highly regulated or monopolised markets).

Both short-term and long-term changes may be studied by the 5-step procedure presented here. To simplify the description in the following text and in **Figure 1**, we limit ourselves to describe the five steps involved in identifying long-term marginal technologies. The difference is that when studying the long-term, we are looking for changes in capacity, while in the short-term we look for changes in production output within the existing capacity.

Another issue, which may be relevant to take into account when discussing time horizons, is fluctuation in supply and demand, which makes it necessary to separately analyse each specific sub-market in time. For example, if the electricity consumption of a process differs between the hours of peak demand and non-peak hours, the difference will affect the marginal of the peak-load technology rather than the marginal of the base-load technology. Such sub-markets in time are typical for service products. For physical products, they only occur in situations where adequate storage capacity is missing, either due to the nature of the product as for electricity and heat, certain food products and chemical by-products, or due to immature markets, as has been seen for some recycled materials. For such products, it is worthwhile, before venturing further into the 5-step procedure, to ensure that the temporal aspects of the investigated product is well defined. However, such temporal product differentiation is no different than any other product differentiation, which obviously influences what marginal technologies to look for. Formally, the temporal specification of the product belongs to the initial phase of a life cycle assessment, in which the functional unit of the product to be investigated is defined, and it has therefore not been included explicitly in the 5-step procedure described here.

(b) Do the changes in production volume only affect specific processes or is a market affected?

The change studied in a comparative life cycle assessment involves a (marginal) reduction in demand for some processes and a (marginal) increase in demand for other processes in the studied product systems. If the resulting changes in production volume can be shown to affect only specific unit processes, the technologies of these processes are - per definition - the marginal technologies, and the 5-step procedure is cut short here. If the change influences a market, one must proceed to identify the marginal technology of this market, which is the purpose of the following steps c-e of the procedure.

The distinction made here is parallel to the distinction of some authors (CLIFT et al., 1998; TILLMAN et al., 1998) between foreground and background processes, and it provides a clear way of identifying whether a process belongs to the foreground or the background of a given product system. A process belongs to the foreground of a system - and should consequently be modelled by site-specific data - if, and only if, its production volume is affected directly by the studied change.

This may be the case if two or more companies are tied closely together in a supply chain and the production volumes of the specific suppliers fluctuate with the demand of the specific clients. Many examples can be found of this situation, and it is very common in the building industry, glass industry, forestry industry, and other industries with products that have a high weight compared to their price.

Note that if the production volume of the specific supplier does not change, this is because the change in demand is transferred on to other suppliers on the market, in which case the remainder of the 5-step procedure must be followed. This may happen in spite of close relations between supplier and client, even in spite of ownership relations or sole-supplier-status, i.e. it is not the closeness of the relation, which is important, but whether the production volume of the supplier is actually affected.

An example of this is in-house electricity production, which may be regarded as the marginal electricity source if the in-house production takes place on non-market conditions, i.e. if the in-house production fluctuates with in-house demand and is not affecting the production volume of the general electricity market. The aluminium industry is well known for their argument that their electricity supply is dominantly hydropower (see e.g. FREES & WEIDEMA, 1998). However, the use of hydropower by the aluminium industry does affect the market, since the availability of hydropower is generally constrained and due to its very low production costs it is anyway utilised to its maximum capacity, disregarding any changes in the volume of aluminium production - with some exceptions such as Iceland and Ghana, where there is no other immediate customer to the generated electricity. Thus, with the exceptions mentioned, the electricity generating technology actually affected by a change in production volume of the aluminium industry is identical to the marginal of the general electricity market.

This means that credit – and incentive – is only given for a shift to products or suppliers with more environmentally friendly technologies, e.g. "green electricity", when this shift actually leads to an increase in the capacity of the "green" technology. If the shift only pretends to be an improvement, and no change is made in the composition of the overall output, no credit is given.

(c) What is the trend in the volume of the affected market?
If a market is affected, we must determine whether we are to look for the marginal of an increasing market or the marginal of a decreasing market, since these are typically not identical. If the market volume is generally decreasing more than the decrease resulting from regular, planned phasing out of capital equipment, the affected technology will typically be the least preferred (old, non-competitive) technology. If the market volume is generally increasing (or decreasing at a rate less than the average replacement rate for the capital equipment), new capacity must be installed, typically involving a modern, competitive technology. Further elaboration on this, as well as a procedure for determining the specific technology affected, is given under steps d-e.

It follows from the above distinction, that if the general market volume is decreasing at about the average replacement rate for the capital equipment, the marginal technology may shift back and forth between two very different technologies, which makes it necessary to make two separate scenarios. This may be relevant for a fairly large interval of trends in market volume, since the replacement rate for capital equipment is a relatively flexible parameter (planned decommissioning may be postponed for some time, e.g. by increasing maintenance).

The trends in market volumes should preferably be determined using the same kind of information as that available to those deciding on capacity adjustments in the affected industry. This information is typically a combination of statistical data showing the past and current development of the market and different forecasts and scenarios. When economic and environmental preferences overlap, the use of forecasts on future market volumes to identify a specific technology as the most or least preferred might have the effect of reinforcing the forecasted trend. Such possibilities for making the forecasts self-fulfilling should be taken into account when deciding the emphasis to place on a specific forecast.

Introduction to steps d) and e)
So far, the procedure has focused on defining the situation, in which the capacity adjustment will occur. In a given situation, one must then go on to ask which technology will actually be the object of the desired capacity adjustment. To answer this question, it must be understood how decisions on capacity adjustment are made. Such decisions are typically based on considerations of expected, relative production costs within a number of constraints. The distinction between constraints and costs is not completely sharp, since some constraints may be translated into additional costs and some costs may be regarded as prohibitive and therefore in practice function as constraints. However, if not taken too strictly, the distinction is useful for practical decision making.

Also the definition of costs itself is not sharp, since concerns for flexibility (as a concern for future costs), environmental costs and other externalities – monetarised or not – may enter the decision-making process.

When predicting the actual decisions with regard to capacity adjustment, it is therefore necessary to include all those constraints and non-monetarised costs which are relevant to the decision maker, but on the other hand not such which are not going to influence the actual decisions. The kind of costs included may also vary depending on the interests of the decision maker, e.g. private investors may place less emphasis on environmental externalities than a public investor. See also FRISCHKNECHT (1998) for a discussion of this.

Thus, what determines a specific technology as marginal is its long-term production costs, taking into account constraints and non-monetarised costs, as perceived by those who decide about the capacity adjustment in question.

Dividing this into two questions, one on constraints and one on costs, we may go on to ask for each of the possible technologies:

(d) Does this technology have a potential to provide the desired capacity adjustment?
The purpose of this question is to eliminate from further analysis those technologies, which do not have a potential to be the marginal technology. Since the marginal technology is – per definition – the technology that changes its capacity in response to changes in demand, a technology which is constrained to its existing capacity – or to a fixed rate of change in capacity – can never be the marginal technology.

For example, in search of the marginal fertiliser technology we may quickly dismiss animal manure, since the production of animal manure is not influenced by changes in demand for fertiliser. Regarded as a fertiliser production technology, animal manure is constrained by the availability of a market for the co-product (animal meat and milk etc.), which may even be further constrained by political limits (e.g. quotas). Thus, in comparisons of products from modern, high-input agriculture, artificial fertiliser production can be identified as the marginal technology to apply.

There may be many reasons for a technology to be constrained in its ability to adjust its capacity either upwards or downwards in volume or in both directions:

- Natural capacity constraints (e.g. the amount of water available in a specific region)

- Quality constraints (e.g. minimum requirements on the quality of the product or its production method)

- Political constraints (e.g. emission limits, quotas, ban on specific technologies)

- Missing markets for co-products (e.g. co-generated heat, animal products as mentioned in the above example)

This list of possible constraints is not intended to be exclusive, but serves as illustration only.

(e) Is this technology the preferred object of the desired capacity adjustment?
Among the unconstrained technologies, we may finally point out the preferred ones, i.e. the ones that will actually be affected. As explained under step c, the technology we are looking for is either the most likely to be installed (in case of an increasing market) or most likely to be phased out (in case of a market, which decreases more quickly than the replacement rate of the capital equipment). The technologies which are most likely to be affected we call the most or least preferred technologies, and what determines these preferences is typically the expected production costs per unit over long-term. As already mentioned above, the expected production costs may be influenced by concerns for future flexibility, environmental costs and other externalities, whether monetarised or not. The important point is to model as closely as possible the actual decision making context of those deciding about the capacity adjustment.

3 Application of the Procedure to the European Electricity Scenario

In the following, the procedure suggested above will be applied to the EU electricity production in general. The presented example was first developed for a specific life cycle assessment on packaging systems for beer and soft drinks (WEIDEMA et al., 1997; FREES et al., 1998), in which we invited an international panel of experts to advice us on the choice of technological level for the study, especially concerning the electricity production scenarios. The recommendations of the international panel, which inspired us to the 5-step procedure presented in this paper, has been published elsewhere (EKVALL et al., 1998).

a) Time horizon
In this example, only the long-term, base-load marginal will be considered, thus answering question (a) in the procedure.

b) Specific processes or a market
In the case of electricity it is obvious that the product is delivered through a market, so that the steps (c) to (e) of the procedure are necessary (we do not discuss here the potential possibility of setting up sub-markets allowing the purchase of electricity from a specific source or technology).

c) Trend in market volume
The production volume of electricity has been generally increasing for the last decade both in the EU and in each national sub-market (Eurostat, 1997b; OECD, 1997). Forecasts of the electricity demand do not suggest any decrease in the coming years, neither in the EU, nor in any of the national sub-markets (European Commission, 1996). Thus, the marginal technology that we are looking for is the most preferred technology (the unconstrained technology with the lowest, long-term production costs).

d) Constraints on capacity increase for the involved technologies

The technologies involved for large scale electricity production are nuclear, hydro, coal, oil, natural gas, biomass, waste and wind power, either as "pure" electricity production or in co-generation with heat.

Many of these technologies are currently constrained, i.e. their production capacity can not be expanded to the extent desired, due to natural capacity constraints, political constraints, or the lack of a market for co-products:

For nuclear power plants it is not likely that new plants will be built within 10-15 years (European Commission, 1995; 1996; 1997). Some countries, e.g. Sweden, even plan a reduction. Hydropower is limited by the areas available for establishing new plants (European Commission, 1997), which may be regarded as a combination of political constraints and natural resource constraints. Even if nuclear and hydro capacity should increase, it will be a planned increase as a result of political decisions upon which small changes in market volume will have little influence.

Fossil fuels (coal, oil and natural gas) are not generally constrained, but may be constrained in individual countries by the emission quotas, especially the SO_2, NO_X and CO_2 targets. This implies that the most polluting technologies in these respects (i.e. especially lignite combustion but also hard coal and oil) may be constrained by these quotas. Lignite may furthermore be constrained by the EU policies for environmentally sound and sustainable energy (European Commission, 1995). No development programs seem to support lignite, as is the case for other fuels and renewables (European Commission, 1995; 1997).

Biomass as an energy source may still expand its market share, but will eventually become limited by the availability of suitable land areas (in competition with other uses of land).

Waste as an energy source is limited by the availability of the resource (waste).

Wind power is currently expanding its market share, but the development is still constrained by the availability of technical knowledge. When this constraint is overcome, there is a fairly large expansion potential before new constraints are met, due to the limited storage capacity of the intermittent wind source (which does not allow wind to be the only source for electricity generation), and due to the limited availability of areas where wind turbines are accepted for aesthetic reasons.

Co-generation of electricity and heat has a potential for expansion, both in new installations and in many existing power plants, which have a significant heat surplus. However, the decision to utilize the surplus heat is determined mainly by the availability of a local market for the co-product (heat) and is independent from the choice of technology for the general electricity market.

Thus, the technologies which have a potential to be the marginal electricity source are the fossil fuels and for a period biomass and wind, since they fulfil the condition of being unconstrained in potential production capacity. However, country specific constraints due to emission quotas may influence which fossil fuel is the marginal for each sub-market. In most of the EU, lignite based power plants are no longer built. An exception may be Greece, where lignite power plants produce most of the electricity supply without indication of decline (Eurostat, 1997a). In the Nordic countries, the emission quotas do not leave room for much expansion of coal based power plants. At present, new power plants planned are natural gas fired (Nordel, 1996).

e) Preferences based on potential production costs

The production costs are composed of fuel costs, operation and maintenance costs, and depreciation of capital goods (→ *Table 1*). The production costs have been calculated for modern technologies, relevant for new plants. To avoid unnecessary work, calculations have only been made for such technologies, which may have a potential to be the marginal electricity source following the considerations above.

Data on fuel costs were supplied by Danish power plants (Larsen, pers. comm.). Operation and maintenance costs and capital costs are taken from Energistyrelsen (1995). An interest rate of 6% has been used. Due to fluctuation in demand, power plants operate on average at less than full capacity. In the calculations, 50% capacity utilization is assumed. The efficiencies of the plants are for electricity production only, since co-production of heat is not relevant for marginal electricity production, for reasons stated above. For windmills, roughness class 1.5 is assumed giving 29% of the theoretical maximum capacity.

The results are verified with data published by Hammar (1997). The price and maintenance of the wind turbine is verified by wind turbine manufactures. In general, the uncertainty on the total costs in **Figure 1** is +/- 10% or lower and dominated by the uncertainty on the capital investment. The resulting ranking of the technologies based on production costs is therefore stable.

From the calculations in **Table 1**, the marginal technology would, under standard conditions, be hard coal or wind power. However, wind power can not at present be regarded as an unconstrained technology, see step d) above.

Provided a deregulated electricity market with adequate transmission capacities – implying the same marginal technology all over the EU – and provided that the EU emission targets do not generally limit the use of hard coal, coal condensing power will be the EU marginal power source, since it has the lowest cost of the unconstrained technologies.

However, as the emission targets are tightened, and the electricity consumption continues to rise, installation of new coal power plants will be constrained, as is currently the case in

Table 1: Calculation of production cost per MWh for modern electricity production technologies

Fuel type	Plant type	Efficiency	Life time	Product per year	Capital investment		Operation and maintenance		Fuel			Total cost
	MW	%	Yrs	MWh/yr	DKK/ MW	DKK/ MWh ***	% of investment per year	DKK/ MWh	Calorific value in MJ/kg	Price in DKK/kg	Cost in DKK/MWh	DKK/ MWh
Hard coal	400	47	30	1.75E6	8E6	110	3.2	59	25.1	0.28	84	250
Nat. gas	15	36	25	6.6E4	5E6	82	2.5	59	39.6 (MJ/m³)	1.3 (/m³)	330	470
Nat. gas	250 CC*	54	30	1.1E6	5E6	68	2.5	34	39.6 (MJ/m³)	1.3 (/m³)	220	320
Heavy fuel oil	15	43	25	6.6E4	6E6	99	-	100**	40.6	0.69	140	340
Bio-mass	250* CFB	45	30	1.1E6	8E6	110	4	73	17.5	0.53	240	420
Wind	0.6	-	20	1500	6E6	220	1.5	36	-	0	0	250

* CC: Combined Cycle in which a natural gas driven turbine and another turbine driven from steam produced from the exhaust gas of the gas turbine.
CFB: Circulating Fluid Bed. Technology at experimental stage

** Authors' estimate. Total cost 250-320 DKK/MWh according to HAMMAR (1997) excl. capital goods

*** Includes a factor 1.8 on the values from the previous column to take into account 6% interest on the investment over 20 years

the Nordic countries. The current marginal technology in the Nordic electricity system is therefore natural gas power. Due to the lower capital costs required, gas fired plants may also be the marginal technology under periods of high interest rates. An exception at the other end of the spectrum is the present situation in Greece, where lignite may still be regarded as the marginal power source.

In most future energy scenarios, fossil fuel prices are expected to increase, as a reflection of increased costs of extraction. Coal prices are expected to increase less than the price of other fossil fuels (European Commission, 1996). This means that the above conclusion – coal power as the general marginal technology, combined with natural gas where emission targets are reached – is relatively stable in time. Furthermore, the rising fossil fuel prices mean that it can be predicted with a high degree of certainty, that wind power will become relatively more competitive, and will eventually become the marginal electricity source for a period, until its expansion potential is limited by the need for a stable back-up technology. Then a period of simultaneous expansion of fossil and wind power may follow until all acceptable sites for windmills have been used. Predictions beyond this will be highly speculative, since both political constraints and trends in electricity use may change.

4 Another Example: Pulp and Paper

a) Time horizon
Also in this example, we focus on the long-term marginal. Since storage capacity is no problem, a difference between peak-load and base-load does not apply.

b) Specific processes or a market
The price of cellulose wood fluctuates very heavily, following a similar fluctuation in price of the final products (BERGSTEDT, pers. comm.). This reflects that there is little alternative outlet for cellulose wood, giving us an example of a situation where the marginal supplier can be identified as a relatively dependant, local, site-specific process.

The final paper products are typically sold on free markets, although most trade takes place on regional markets due to the high transport costs.

c) Trend in market volume
The market has been increasing worldwide, with the exception of a sudden decline in East Europe and the former USSR after the change of political regime (FAO, 1997).

d) Constraints on capacity increase for the involved technologies
None of the available technologies for pulping virgin fibres are constrained. For recycling, you can generally say that on an increasing market, recycling will always be upwards constrained by the availability of recycled material. In practice, the amount of recycling will be constrained by the characteristics of the collection system, including the relative costs of collection to virgin material, with an upper limit depending on the loss of quality in the cycle.

e) Preferences based on potential production costs
Thus, focusing on the unconstrained technologies for virgin fibres, we note that the main factor influencing production costs is a very important economy of scale (TSUOMIS, 1991), which leads to a preference for expanding the existing plants

– whatever their technology (KARLSON, pers. comm.). Thus, constrained to the technology once installed, the marginal technology differs from region to region. For example, from the Danish import statistics it can be seen that 90% of all Danish paper comes from Sweden and Finland, where the sulphate-process is dominating, while the German market is dominated by the sulphite-process (BERGSTEDT, pers. comm.). Because of the particular situation of very local markets each with their quite uniform technology, there are no big differences between the marginal technologies and the regional average technologies, but this is clearly a special case.

The different technologies have different demands for raw material, the sulphate-process being the most flexible (TSUOMIS, 1991; BERGSTEDT, 1994). If eventually, there is a need for new plants, a long-term consideration for productions costs and competitiveness is likely to result in a preference for this flexible technology.

5 Further Examples

The purpose of the examples presented above has been to illustrate the suggested 5-step procedure and to demonstrate the feasibility of determining marginal technologies. The examples do not cover particular local situations, which may deviate from the overall results presented here. Current research performed at our institute and funded by the Danish Environmental Protection Agency will provide further examples and recommendations on the relevance of the procedure and how to identify the marginal production facility in specific situations. We welcome other interested researchers to join this work.

6 Discussion and Conclusion

It is worth noting that in order to model the consequences of a decision, it is not necessary to know in advance which specific products will substitute each other as a consequence of the decision. Using data on marginal technologies for a specific product will provide information on the actual consequences of any marginal change involving the studied product, i.e. the consequences of any possible substitution as long as it remains small so that the *ceteris paribus* condition is fulfilled.

If the extent of the product substitution is large, the *ceteris paribus* condition is no longer fulfilled and the studied change can no longer be regarded as marginal. This means that the change may affect the overall trends in market volumes, as well as the constraints on and production costs of the involved technologies, so that a different technology will become the preferred one for the large capacity adjustments required. In this case, the 5-step procedure will still be relevant, although the term marginal will no longer apply to the technology identified by the procedure.

The examples presented in this paper demonstrate that identifying marginal technologies is not particularly difficult when using the proposed 5-step procedure. Once the marginal technology has been identified, only environmental data for this technology need to be collected, saving much time compared to collection of average data, where the environmental data of several technologies must be combined.

Since marginal data change only with changes in the boundary conditions (constraints and long-term expected production costs) or with developments in the marginal technology itself, the resulting data are more stable in time than corresponding average data, which change with every minor change in capacity.

Compared to marginal data, which always relate to a well-defined technology, average data are more uncertain, not only because of the mentioned variability in time, but also because of their inherent uncertainty, resulting from combining a large number of data for different technologies and conditions, often from different sources. This uncertainty is further enhanced if the average data relate to a process with more than one product, in which case it is necessary to use an uncertain allocation ratio to partition the environmental inputs and outputs of the process among its co-products. Such allocation issues can often be avoided when using marginal data.

Recalling again that marginal data reflect better the actual consequences of a decision, there remains very little reason for using average data in comparative life cycle assessments.

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Conference Announcement

Atmospheric Reactive Substances – Environmental Relevance of Natural and Man-Made Contributions

First International Symposium, 14-16 April 1999, Universität Bayreuth, D-95440 Bayreuth, Germany

Organized by the Joint Expert Group on Atmospheric Chemistry of GDCh, DECHEMA, and DBG, under participation of FECS-CE. Supported by the German (UBA) and Swiss (BUWAL) Federal Environmental Agencies, and the European Community (EC).

The scope of the symposium shall over assessments of the relative significance of the sources of man-made and natural precursors, the mechanisms and pathways of formation of reactive substances, the reliability of analytical methods for monitoring of environmental levels and of the data obtained, and the assessment of the potential impact of ARS on the biosphere, including hazards to humans.

Major contributions to atmospheric reactive substances are precursor emissions from

a) refining of crude oil, production, distribution, and use of hydrocarbon fuels for automotive transport,
b) production and use of solvents, diluents, propellants, blowing agents etc. in various industries, e.g., in textile, fine-mechanic and electronic industries, and
c) natural biological sources, predominantly marine and terrestrial plants.

Discussions and exchange of views and scientific findings by scientists and specialists of the relevant industries, from universities and research institutions, and from environmental agencies are therefore the central goals of the symposium. Each of the topics will be introduced by internationally renowned speakers. In order to attain the utmost level of scientific interaction between all participants, ample time will be devoted to discussion sessions, including the posters.